Chapter 1
INTRODUCTION

1.1 Background

Keeping cool in hot climates has long been a human preoccupation. For thousands of years, people have used a variety of architectural techniques (thermal mass, shading, strategically-placed vents, atria, etc.) to adapt dwelling design and cultural practice to local climate conditions. After the industrial revolution, many of these techniques were adapted to the new requirements of large buildings. The tradition of massive, daylit buildings, with courtyards and airshafts, is still visible today in older European and North American office buildings, especially in the south.

In 1902, while searching for a method to control humidity in a printing plant, Carrier invented the refrigerative chiller. Within a few years, the world had access to a device that could cool any boxy, sealed building, regardless of how much heat it gained and trapped [1]. However, the mechanical cooling of buildings did not become widespread in the United States until after World War II. As the electrification of the American South progressed, air-conditioning was first introduced in movie theaters, then made its way into factories, homes, offices, department stores, even automobiles. By the 1950s, the reliability of air-conditioning, the adoption of fluorescent lights and of solar control glazing, and the steadily falling price of electricity, allowed architects throughout the country to abandon the ancient techniques of climate-responsive design, and to focus on the artistic side of design instead. Today, even portions of outdoor facilities (football stadiums, zoos, amusement parks, etc.) are air-conditioned. Air-conditioning is ubiquitous; its presence has become the expected norm.

In the 1950s air-conditioning played a significant role as stimulus to commercial and residential growth in the American Southwest. Since then, it has evolved from a region-specific solution to a perceived necessity virtually nationwide. One of the consequences of today's intensive use of air-conditioning is that building professionals have lost much of their ability to design climate-responsive buildings. The compartmentalization of the building profession [2], and the divergent interests of the different parties involved in the building process, make modern buildings costlier to build, and considerably costlier to cool and ventilate than need be. In addition, worker surveys reveal that commercial building occupants are increasingly dissatisfied with the thermal conditions of their workplace [3], and that occupant exposure to air-conditioned indoor environments sometimes leads to adverse health conditions [4]. When trying to address these problems, innovative designers have begun to recognize the importance of restoring some natural variability into buildings, thereby making interior spaces healthier, more pleasant, and often more energy efficient. However, due to the same divergence of interests among the parties involved in the building process, this attempt to return to a climate-responsive design is slow and inefficient.

Another consequence of the widespread use of air-conditioning in the United States is that, although air-conditioning is responsible for only 12% of the total building energy consumption [5], its electrical power demand is considered to be “the load from hell” [6]. Because the electricity demand due to space cooling is high and seasonal, it forces utilities to make investments in power generation equipment that is only used on the hottest days of the year. The cost of this inefficient capacity is then passed on to all utility ratepayers, whether they own an air-conditioning system or not. In addition, the costs of increased emissions from electricity production, and the environmental costs of chlorofluorocarbon (CFC) use in air-conditioners, are borne globally [7].

A last consequence is that increased use of air-conditioning in the developing countries will multiply local and global environmental problems. In Southeast Asia, for example, the need for mechanical cooling is often secondary to the desire to demonstrate social status or international stature through the acquisition of modern technology. But the adoption of the “good american life” imposes the comfort standards developed in temperate regions on individuals that were previously adapted to hot and humid climates. This reduces their tolerance for heat and humidity, forces their acclimatization to artificially-created conditions, and ultimately results in a waste of energy and resources [8]. The use of air-conditioning in the developing countries can only exacerbate the local energy and global environmental effects.

One step towards resolving this complex set of interlocking problems would be to reformulate the “expected norm” in a way that would encourage climate-responsive design all around the world. However, while current energy and environmental problems are at a scale that would benefit from swift and effective action, the adoption of climate-responsive design would likely take a long time. Furthermore, this solution would not address the problems associated with the operation of the numerous energy-intensive buildings that are already in use. As an alternative solution, much attention is dedicated today to incorporating energy efficient technologies in building design. Although this course of action does not influence the “expected norm” directly, it addresses the energy and environmental problems to some extent, and it is beneficial for new construction and retrofit projects alike.

Anticipating the problems that may be caused in the future by current building design, the US Office of Technology Assessment (OTA) indicated that the use of cost-effective, commercially available technologies in the United States could reduce total building energy use by about one-third by 2015, relative to a business-as-usual baseline [9]. One of the actions recommended by the OTA to achieve this goal is the reduction of the efficiency gap between the average new cooling equipment and the most efficient cooling equipment available: substituting the average new cooling equipment with energy efficient cooling equipment can save up to 28% of the US energy consumption due to space conditioning [5]. The OTA recommendations were corroborated by Feustel and collaborators [7], who showed that alternative cooling technologies can reduce the energy consumption and peak power demand due to space conditioning while striving to provide indoor conditions very similar to those provided by the compressor-driven technology.

Severe urban air pollution, high energy prices, and concerns about energy security have prompted Western European countries to encourage the reduction of building energy consumption and peak power demand through the adoption of new building standards. These standards call for better building design in general, and for the replacement of the traditional all-air systems with alternative, more efficient building conditioning systems in particular. At the recommendation of the OTA, similar efforts are currently in progress in the United States, carried out under government and/or utility sponsorship. However, while alternative cooling technologies and sources[1] are intensively used in new construction and retrofit projects in Western Europe, the relatively low energy prices in the US, together with the decentralization and fragmentation of the building industry, have so far been a barrier to the large-scale implementation of alternative cooling technologies in the United States.

1.1.1 Motivation for this research

While examining the literature that addresses the issue of alternative cooling technologies in Western Europe and the US, Feustel and Stetiu [10] noted the conspicuous absence from the US market of radiant cooling, an alternative cooling technology that is currently implemented in Western European commercial buildings. A complete explanation for the absence of radiant cooling systems from the US market would very likely require the description of a complex interaction of technical, economic, social, and cultural factors. Instead of addressing this ambitious task, this thesis investigates whether, and how well, radiant cooling systems could perform in commercial buildings in the US, discusses the economics governing the US air-conditioning market, and identifies the type of policy interventions and other measures that could encourage the adoption of radiant cooling in this market.

The available information regarding the performance of radiant cooling systems indicates that these systems not only reduce the energy consumption and peak power demand due to space conditioning, but that they also provide draft-free and noise-free cooling, reduce building space requirements, and might even have lower first-cost if maximum specific cooling loads are above 50 - 55 W/m^2. By using back-of-the-envelope calculations, Feustel and Stetiu estimated that the use of radiant cooling systems in commercial buildings in the US could reduce the building energy consumption due to space conditioning by 40% and the peak power demand by 28%.

Radiant cooling systems provide thermal comfort inside a building by means of radia-

1. Alternative cooling systems available on the Western European market are evaporative cooling, desiccant cooling, absorption cooling and radiant cooling. Commonly used cooling sources (or heat sinks) are natural cooling and ventilation, cooling towers, and ground coupling.

tive heat exchange with a cold surface, and maintain acceptable indoor air quality by supplying the necessary amount of fresh air with an air distribution system. By separating the tasks of thermal conditioning and ventilation, radiant cooling systems eliminate air recirculation, thus reducing the energy consumption due to space conditioning. However, the presence of a cold surface in a space increases the risk of condensation, a phenomenon unacceptable from the point of view of occupant comfort, as well as because it can damage the building structure, building finishes, and the radiant system itself. To prevent the formation of condensation on the cooling surface, radiant cooling systems commonly control the moisture content of the indoor air by dehumidifying the ventilation air. In hot humid climates, the dehumidification of the ventilation air can be extremely energy intensive.

No known research has addressed the climate-compatibility of radiant cooling systems so far, partly because a software tool that can model the thermal behavior of radiant cooling systems in buildings has not been available. There is no doubt that a radiant cooling system can be designed to cool a building located in any climate. However, it is unclear whether the radiant cooling system can prevent the formation of condensation in any climate, and still require less energy and peak power to operate than a traditional all-air system. Because the available data regarding the performance of commercial buildings equipped with radiant cooling systems refer to a few buildings in Germany and Switzerland, it is possible that the European buildings studied so far are located in climates in which radiant cooling systems are inherently more efficient than all-air systems. Therefore, it is currently difficult to argue that installing a radiant cooling system instead of an all-air system in a commercial building located in *any* climate would reduce that building's energy consumption and peak power demand due to space conditioning. The research presented in this thesis is the first in-depth investigation into the climate-related aspects of the performance of commercial buildings equipped with radiant cooling systems. Its results provide information regarding the potential of radiant cooling systems to reduce energy consumption and peak power demand in the typical climates found in the US.

1.1.2 Thesis objectives

The first objective of this thesis is to describe the development of RADCOOL, a simulation tool that can model the dynamic thermal and moisture-related effects associated with the functioning of radiant cooling in buildings. RADCOOL is an original computer model, designed by the author of this thesis to provide information about loads, heat extraction rates, air temperature, and surface temperature distributions in a building. RADCOOL can evaluate system sizing and system configuration, and can assist in HVAC system design. RADCOOL can also be used in the evaluation of issues such as controls, and the dynamic response of the building systems to load changes, and can be extended to study indoor thermal comfort and building energy use. The ultimate goal for

RADCOOL is to operate as a DOE-2[1] module. This would allow building practitioners to access the capabilities of this program through the familiar DOE-2 interface.

The second objective of the thesis is to use RADCOOL in an investigation of the climate-related aspects of the performance of buildings equipped with radiant cooling systems. To accomplish this, the thesis conducts a parametric study consisting of simulating a building with pre-established construction, orientation, occupancy rates, etc., under different weather-imposed boundary conditions. The study is designed to provide two types of results. First, an indication of whether buildings equipped with radiant cooling systems can be operated to avoid side effects such as condensation at any location in the US. Second, an accounting of the energy consumption and peak power demand of the radiant cooling system. The comparison of RADCOOL simulation results with similar simulation results obtained for the same building equipped with a traditional all-air system provides estimates of (1) the energy savings potential of the radiant system, and (2) the dependence of these energy savings on the climate in which the building is located.

The third objective of the thesis is to assess the prospects of radiant cooling capturing a share of the US air-conditioning market. To do so, the thesis discusses the economics of this market, and identifies the measures that would encourage the incorporation of radiant cooling in building design in the United States.

1.2 Thesis Outline

The core of the thesis begins in Chapter 2 with a summary of the present state of knowledge about radiant cooling systems. It contains a short history of radiant cooling, information about the performance of existing buildings equipped with radiant cooling systems, and a discussion of the advantages and disadvantages of radiant cooling systems as compared to traditional air-conditioning systems.

Chapter 3 describes the design, evaluation, and limits of RADCOOL, the computer model developed specifically for the simulation of buildings equipped with radiant cooling systems. Because the simulation of such buildings requires the evaluation of surface temperature distributions, RADCOOL is based on a complete energy-balance calculation. The environment for RADCOOL is the Simulation Problem Analysis and Research Kernel (SPARK) [12], a code that provides a methodology for describing and solving the dynamic, non-linear equations corresponding to complex physical problems. The physical equations that constitute the basis of RADCOOL are presented in Appendix A.

Chapter 4 describes the modeling project designed to evaluate the compatibility between buildings equipped with radiant cooling systems and typical climates found in the US.

1. DOE-2 is a widely-used building simulation program [11]. In its present stage of development, DOE-2 cannot model buildings equipped with radiant cooling systems.

The evaluation consists of RADCOOL simulations for an office space equipped with a radiant cooling system, and DOE-2 simulations for the same space equipped with a traditional all-air system, carried out in parallel for a number of US climates. This chapter contains (1) a discussion of the selection of building design, locations, and simulation periods, necessary because of the computational constraints of RADCOOL, (2) the strategy adopted for comparing the RADCOOL results and the DOE-2 results, and (3) an evaluation of the uncertainties introduced by these operations.

The results of the modeling project and its findings are presented in Chapter 5 and Appendix B. The modeling project was designed to allow the differences between the RADCOOL results and the DOE-2 results to be attributed to the differences between the heat transfer mechanisms employed by the radiant cooling system and the traditional all-air system. This feature provides estimates of the energy and peak power savings potential of the radiant cooling system at each of the locations selected for the study. Based on these results, the energy consumption and peak power demand of the radiant cooling system at a certain location and the energy consumption and peak power demand of the all-air system at the same location can be correlated. As this quantitative relationship is location-dependent, its existence allows the prediction of the savings achievable by installing a radiant cooling system instead of an all-air system at any location (in the US or elsewhere).

To put these results in context, Chapter 6 discusses the economics governing the US air-conditioning market, and exposes the types of policies and other measures that would encourage the adoption of alternative cooling technologies in general, and of radiant cooling in particular, on this market. Drawing from the results of the thesis and the discussion in Chapter 6, Chapter 7 identifies directions for future research.

1.3 References

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